ENVIRONMENT OF THE TERTIARY FAUNAS OF THE PACIFIC COAST OF THE UNITED STATES*†

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XII

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INTRODUCTION

This paper was presented as part of the symposium on "Correlation" arranged by Mr. Bailey Willis as the principal subject for discussion in Section E of the American Association for the Advancement of Science, and later continued as the main feature of a special section of the Geological Society of America, at Baltimore during Convocation Week, 1908. The paper treats in a general way of the character and distribution of the sediments laid down, and the faunas and the conditions prevailing during the Tertiary period on the Pacific Coast of North America, more especially that portion lying between Puget Sound on the north and the Gulf of California on the south. The discussion is also restricted almost exclusively to the territory directly affected by the sea, as a detailed consideration of the conditions and faunas prevailing inland belongs more properly within the province of the paleobotanist and vertebrate paleontologist. Special attention is called at several places throughout the discussion to the extraordinary localization of many of the earth-movements affecting the region under discussion and the writer wishes to advance this localization of phenomena as an argument against the too free use of diastrophism, unsupported by paleontologic evidence, as a basis of correlation.

The preparation of the paper has necessitated the correlation of the various Tertiary formations of the Pacific Coast—in fact the paper is obviously based on these correlations—and for that reason a general table of correlation is here included for reference. Lack of space prevents a discussion of the reasons for many of these correlations. Some of them differ from those previously published by the writer,[1] but for the most part they are those usually accepted by West American geologists and paleontologists.

[1] *Jour. Geol.*, Vol. X, 1902, p. 137; *Mem. Cal. Acad. Sci.*, Vol. III, 1903, p. 13; *U. S. Geological Survey Prof. Paper 47*, 1906, p. 10; *U. S. Geol. Survey Bull. 309*, 1907, p. 143; *ibid.*, *321*, 1907, p. 21; *ibid.*, *322*, 1908, p. 27.

The fourfold subdivision of the Tertiary is the one which seems best to fit the phenomena of the Pacific Coast, although for convenience of discussion in the present paper the writer has separated the upper from the lower Miocene on account of the diverse geologic histories of the two. It is obviously impossible to make exact correlations between the European and East American subdivisions on the one hand and the faunal and stratigraphic subdivisions of the Pacific Coast on the other, but by means of various direct and indirect methods it is possible, however, to make approximate correlations, and as the work progresses these approximations will be made to approach nearer and nearer to the exact. Paleontology forms the basis for the correlations, but other criteria, such as periods of widespread diastrophism and volcanic activity and profound changes in climate, have also been taken into consideration. It is well to mention here that the total thickness of Tertiary and Quaternary sediments in California approximates 25,000 feet and that within the Tertiary and Quaternary periods, relatively short, geologically speaking, as compared with the earlier divisions of the time scale, probably more distinct and profound movements have taken place on the western border of our continent than have occurred over an equal length of time in any of the preceding periods within the limits of North America.

Five maps have been prepared to elucidate the paper, each respectively representing the supposed distribution of land and water along the western border of the United States during the Eocene, the Oligocene, the lower Miocene, the upper Miocene, and the Pliocene and Pleistocene epochs. It is admitted that these maps are composites; that is, they represent the distribution not at any definite moment but throughout a period of time during which the local conditions usually changed but little relative to the changes taking place between these periods. For instance, the areas shown as subject to deposition during the Eocene are the areas over which deposits were laid down at one time or another during the Eocene epoch. In the case of certain portions of Puget Sound and elsewhere, marine conditions prevailed during the early Eocene, brackish-water conditions a little later, and freshwater or river, and coal-marsh conditions toward the close. In other portions of the same general area the conditions

alternated. It is obvious, therefore, that the legends on the maps are very general. Only in those instances where the body of water indicated as fresh remained fresh throughout practically the whole of its existence is it indicated as a freshwater area on the map.

The periods chosen for representation and as units for discussion are neither of equal length nor of equal importance, and the lines separating them are in some instances arbitrary; but it is believed that they serve the purpose of systematizing the discussion better than any other plan of subdivision. The data are incomplete and the conclusions admittedly tentative, and it is expected that future investigations will disclose new and important information, which will necessitate alterations, but the fact remains that general reports of this kind, based as they are on the present state of our knowledge, often point the way to more exact results in the future.

ACKNOWLEDGMENTS

The writer wishes to acknowledge his indebtedness to Messrs. Bailey Willis, J. S. Diller, T. W. Stanton, Robert Anderson, Chester W. Washburne, and several others for personal assistance in the preparation of the text and maps, and to express his thanks for the services rendered. In addition to the personal aid received, the literature relating to the subject of West Coast geology has been freely drawn on in the compilation of relevant data and in many cases proper acknowledgment for this is made in the text.

THE EOCENE PERIOD

RELATION OF THE EOCENE TO THE CRETACEOUS

Before entering into the details of the geologic history of the Tertiary it is well to consider for a moment the relations existing between the earliest Tertiary rocks and those of the Cretaceous, and to note the conditions initiating the Tertiary, as implied by these relations.

A widespread unconformity exists between the Eocene and the Cretaceous on the Pacific Coast of North America. Throughout Washington, Oregon, and certain parts of California, this unconformity is angular, while over considerable areas in California and at one locality in Oregon the unconformity may only be recognized by a more or less marked hiatus in the faunas.

It is a noteworthy fact that with one exception wherever the line between the marine Eocene formations (Martinez, Arago, Tejon, etc.) and the Cretaceous beds is marked by an angular unconformity, the underlying beds are either of lower Cretaceous (Knoxville) or middle Cretaceous (Horsetown) age, and that wherever the Eocene rests on the Chico, or upper Cretaceous, excluding the case at San Diego, the unconformity is not angular, and as far as the stratigraphic evidence goes, the two formations represent an apparently uninterrupted period of sedimentation.

The apparent conformability of the Eocene on the Cretaceous, together with the superficial similarity of their faunas, led Gabb and Whitney of the early California Survey to class the Martinez and Tejon formations with the Cretaceous. White, Stanton, and Merriam have, however, shown the Eocene age of the Martinez and Tejon. Of the relationships existing between these two and the Chico, or upper Cretaceous, Dr. Merriam has the following to say:

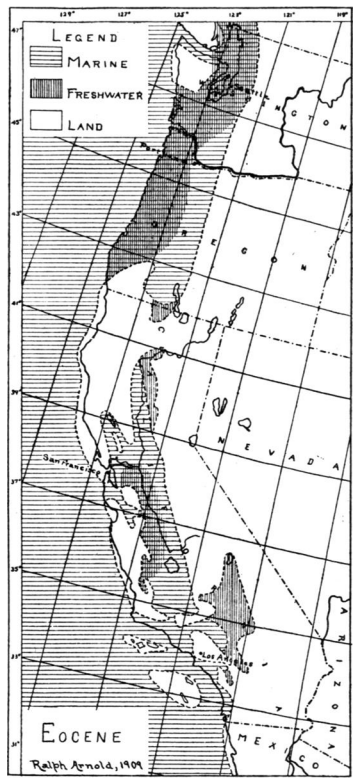

FIG. 1.—Map showing hypothetical distribution of land and water on the Pacific Coast of the United States during Eocene time.

> The Martinez group, comprising in the typical locality between one and two thousand feet of sandstones, shales, and glauconic sands, forms the lower part of a presumably conformable series, the upper portion of which is formed by the Tejon. It contains a known fauna of over sixty species, of which the greater portion is peculiar to itself. A number of its species range up into the Tejon and a very few long-lived forms are known to occur also in the Chico. Since the Martinez and Chico are faunally only distantly related it is probable that an unconformity exists between them.[1]

[1] *Jour. Geol.*, Vol. V, 1897, p. 775.

Another fact showing the relations existing between the Eocene and the Cretaceous is the occurrence in the Eocene beds in the Roseburg region, Ore., of oysters so similar in appearance to the characteristic Cretaceous fossil, Gryphæa, that without their accompanying Eocene fauna these oysters would certainly be mistaken for Cretaceous forms.

CONDITIONS IMMEDIATELY PRECEDING AND INAUGURATING THE EOCENE

Immediately preceding the Eocene period practically all of Washington, all of Oregon excepting a small area along its southern border, the Sierran and desert region, and certain portions of the coastal belt of California were dry land. Most areas in California, and possibly also those in the Puget Sound region, which were occupied by the Chico or upper Cretaceous sea, were still under water, or at least elevated only slightly above sea-level and this without deformation of the Chico beds or subsequent erosion before subsidence. Influences, however, which markedly affected the faunas without materially influencing the sedimentation, were actively at work, and it seems likely that these influences were due to worldwide climatic changes augmented by a readjustment of ocean currents following orogenic movements. In Washington, according to G. O. Smith,

> the deposition of the Cretaceous rocks seems to have been followed by an epoch in which they and older rocks were folded and uplifted. Thus was an early Cascade Range outlined, although it may be that the range had an even earlier origin. Accompanying the post-Cretaceous mountain growth were intrusions of granitic and other igneous rocks which now constitute a large part of the northern Cascades. During the time that any portion of this area was not covered by water the rocks were exposed to the vigorous attacks of atmospheric agencies. Thus, at the beginning of the Tertiary the northern Cascade region appears to have been a comparatively rugged country, although not necessarily at a great elevation above sea-level.[1]

A study of the interrelations of the Cretaceous and Eocene formations outlined in a preceding section clearly indicates that any important pre-Eocene mountain-building movements affecting the Cretaceous rocks in the California province must have taken place before the deposition of the Chico or upper Cretaceous sediments. As shown by F. M. Anderson,[2] the movements immediately preceding

[1] "Ellensburg Folio," *Geol. Atlas U. S., No. 36*, p. 1.

[2] *Proc. Cal. Acad. Sci.*, 3d ser., "Geology," Vol. II, 1902, p. 53.

the deposition of the Chico were accompanied by basic igneous intrusions. No profound movements and no volcanic activity accompanied the post-Chico (post-Cretaceous) movements in California as they did in Washington.

Steep mountains bordered the youthful Eocene sea in southern Oregon, northeastern California, and north of San Diego, and occupied portions of one or more large islands in the region of Monterey and Santa Barbara counties south of San Francisco. Elsewhere the relief of the land appears to have been comparatively low and the shore-lines with few bays or estuaries.

DISTRIBUTION AND CHARACTER OF SEDIMENTS

Rocks of marine origin and Eocene age are found at many localities throughout Washington and Oregon west of the Cascade Range, and over considerable areas of the Coast Ranges in central and southern California. Although Eocene rocks probably once fringed the greater part of the western base of the Sierra Nevada, they are now all removed by erosion or covered by later formations except at one locality near Merced Falls. For the most part the Eocene rocks of the Pacific Coast are either sandstone or shale. Conglomerate is found at the base of the formation throughout southeastern Oregon, north of San Diego, and at a few localities along the northeastern flanks of the Coast Range; and at Port Crescent, Washington, Eocene fossils are associated with tuff; but these occurrences are exceptional. Also, diatomaceous shales occur at the top of the Eocene series in the vicinity of Coalinga, Cal., where they are believed to be the source of important deposits of petroleum. Coal and other indications of shallow- and brackish-water conditions are found over much of Washington and Oregon and California, usually overlying marine Eocene beds. The maximum thickness of the Eocene sediments varies from 8,500 feet east of the Cascades,[1] 10,000 to 12,000 feet in western Oregon[2] to 9000± feet in southern California.[3]

CONDITIONS PREVAILING DURING THE EOCENE

During the early part of the Eocene, marine conditions prevailed over a considerable territory that later was covered by brackish- or

[1] G. O. Smith, *Mt. Stewart Folio.*

[2] J. S. Diller, *Roseburg, Coos Bay, and Port Orford Folios.*

[3] Ralph Arnold, *U. S. Geol. Surv. Bull. 321*, p. 21.

freshwater or swamp conditions. The regions thus affected include a large part if not all of the Puget Sound and western Oregon provinces and a considerable part of central California. How far these conditions extended eastward into central Washington and Oregon it is not possible to state owing to the covering of the Eocene by later volcanic flows. It is quite possible, however, that certain portions of the Sound country was at no time submerged under salt water, or if at all only for very short periods, for Willis states[1] that coal occurs both in the basal and upper portions of the Puget formation, which is believed to cover the period from the Eocene into the Miocene. He states further that "the physical history which is recorded in the Puget formation is one of persistent but frequently interrupted subsidence" in which "the alternation of coal beds with deposits of fine shale and coarse sandstone indicates that during this great subsidence the depth of water frequently changed." He infers "that at times the subsidence proceeded more rapidly, and that the deepened water was then filled with sediment, until the tide-swept flats became marshes, and for a time vegetation flourished vigorously in the moist lowlands," this rotation being repeated intermittently. This description of conditions is believed also to apply to much of Alaska, western Oregon, and portions of the interior valley of central California during the later Eocene. The epicontinental Eocene seas were for the most part rather shallow and in the later Eocene particularly were bordered by wide tide flats and marshes.

In the region of Lower Lake in Lake County, Cal., in the Mojave Desert immediately north of the Sierra Madre, and in the vicinity of San Diego, the early Eocene (Martinez) sea was present, but later receded and these particular areas are believed to have been dry land during the later Eocene. The Mojave Desert basin may have been covered with freshwater at this later period as lake deposits believed to be largely of Eocene age are known from the region contiguous to it. This would be in accordance with the conditions prevailing in eastern Oregon[2] and Washington[3] where great lakes existed during Eocene time immediately east of what is now the Cascade Range,

[1] *Tacoma Folio*, p. 2.

[2] J. C. Merriam, *Bull. Dept. Geol. Univ. of Cal.*, Vol. II, No. 9, p. 286, 1901.

[3] G. O. Smith, *Mount Stewart and Ellensburg Folios*, Washington.

and possibly also east of the Sierra Nevada. Erosion tending toward a base-leveling of the Sierra Nevada and other elevated portions of the Pacific Coast must have proceeded rapidly during the Eocene as is evidenced by the great thicknesses of strata laid down during the period and by the fact that high relief was not present during the Oligocene except in rare instances, although the Oligocene in general was a period of uplift for much of the Pacific Coast province.

OROGENIC MOVEMENTS AND VOLCANIC ACTIVITY IN THE EOCENE

After the deposition of the early Eocene came a period of temporary elevation, erosion, and great volcanic activity in Washington, Oregon, and northern California. Extensive basaltic eruptions through long conduits and over the eroded rock surfaces took place in eastern Washington and western Oregon, while in the region of the Olympic Mountains and eastern Oregon basalt flows and volcanic outbursts were also taking place. Eocene volcanic disturbances so pronounced in the north do not appear to have affected the Sierra Nevada nor the coastal region of California south of the Klamath Mountains.

CLIMATE DURING THE EOCENE

The faunas and floras of the Eocene indicate subtropical conditions for this period at least as far north as Puget Sound. The marine faunas of the Pacific Coast Eocene are closely allied to those of the Eocene of the southern states and the Eocene shells, *Corbicula*, for instance, as a rule belong to groups showing a predilection for warm waters. This supports the evidence offered by the floras which are of a decidedly tropical aspect. Doctor Knowlton has the following to say in connection with the flora of the Puget formation, which may be regarded as typical of the Washington, Oregon, and California Eocene:

> The lower beds [the Eocene portion of the Puget formation], on account of the abundance of ferns, gigantic palms, figs, and a number of genera now found in the West Indies and tropical South America, may be supposed to have enjoyed a much warmer, possibly a subtropical, temperature, while the presence of sumacs, chestnuts, birches, and sycamore in the upper beds [Oligocene and lower Miocene] would seem to indicate an approach to the conditions prevailing at the present day.[1]

[1] *Tacoma Folio*, p. 31.

THE OLIGOCENE PERIOD

THE OLIGOCENE A PERIOD OF ELEVATION

The Oligocene on the Pacific Coast was primarily a period of elevation and erosion over many areas which are now land. As indicated by the fine character of most of the sediment deposited during the period, the relief was not strong, except in a few regions. Outside the Washington - Oregon province there are few evidences of the period, except a more or less marked unconformity between the Eocene and lower Miocene, and these for the most part are on the extreme continental border or along the edges of the provinces of persistent subsidence. The extreme localization of the post-Eocene movements is well shown in the southwestern San Joaquin Valley where the lower Miocene and Eocene are apparently conformable and again occur within a distance of a quarter of a mile separated by a profound angular unconformity. Strata of undoubted Oligocene age consisting largely of sandy to clayey shales and carrying a characteristic marine fauna are found at many localities throughout the Puget Sound and northwestern Oregon areas and an isolated occurrence of similar beds is found in the Santa Cruz Mountains, a short distance south of San Francisco. Wherever their relations are known these beds lie conformable with the Eocene below and lower Miocene above; they therefore mark areas of persistent subsidence. A characteristic reddish to lavender formation (the Sespe), consisting of sandstone, shale, and some conglomerate found in Ventura and Los Angeles

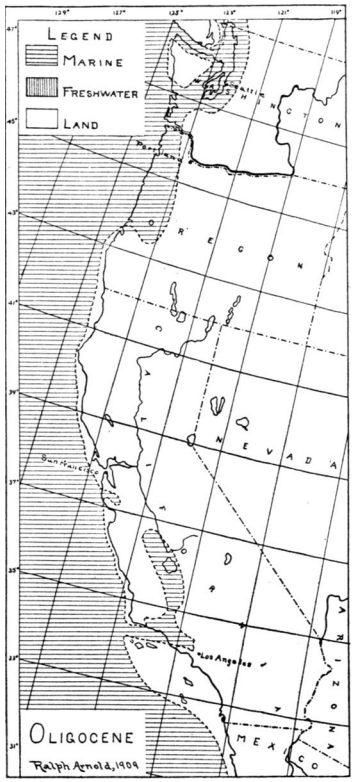

FIG. 2.—Map showing hypothetical distribution of land and water on the Pacific Coast during Oligocene time.

counties in southern California, has been doubtfully referred to the Oligocene and the map made to agree with this correlation; but it is possible this formation is Eocene.

Certain marine shales and sands underlying the lower Miocene beds in western Fresno and Kern County may also belong to the Oligocene. If so they imply that an arm of the sea remained in the San Joaquin Valley following the post-Eocene elevation that excluded marine conditions from much of the coastal belt of western America.

The total thickness of the Oligocene over the region where it has been recognized varies from over 1,000 feet in Washington to 2,300± feet in the Santa Cruz Mountains. The Sespe formation of Ventura and Santa Barbara counties, which has been tentatively correlated with the Oligocene, attains a maximum thickness of about 4,300 feet.

CONDITIONS OF EROSION AND DEPOSITION

With the close of the Arago stage (Eocene)[1] the Klamath Mountains and Coast Ranges of Oregon and California were uplifted to a moderate elevation and subjected to extensive erosion, in some localities completely removing the sediments deposited during the Eocene. With the possible exception of an area in Ventura County in southern California no mountains of strong relief contributed directly to the Oligocene sediments. In eastern Washington the great lakes which prevailed during the Eocene were elevated and the sediments which had been deposited in them were folded and eroded, the resulting detritus in addition to large quantities of volcanic ejectamenta being collected in bodies of freshwater in eastern Oregon farther south. It is thus known that with the elevation of this northern country volcanic activity still continued although on an insignificant scale as compared with the periods preceding and following the Oligocene. In California there is no evidence of volcanism in the Oligocene period.

FAUNA AND CLIMATE OF THE OLIGOCENE

What little is definitely known concerning the faunas of the Oligocene as a whole indicates their closer affiliation to the Miocene than to the Eocene. The fauna from the Oligocene of the Santa Cruz Mountains (San Lorenzo formation) and a similar fauna from

[1] J. S. Diller, *Roseburg Folio.*

Porter near Grays Harbor, in western Washington, are believed to be the oldest of the definitely known Oligocene. In these assemblages are several species showing distinct Eocene affinities; in the later Oligocene the forms are decidedly more closely allied to Miocene forms. The climatic conditions prevalent on the west coast of the United States during the Oligocene are believed to have been transitional from the subtropical of the Eocene to the more temperate of the lower Miocene.

THE LOWER MIOCENE PERIOD

CONDITIONS INAUGURATING THE LOWER MIOCENE

The Oligocene period of elevation and moderate erosion was followed by diastrophic movements of a most interesting and important character. It was during this post-Oligocene period of disturbance that definitely recognizable movements along what is now termed the great earthquake rift and associated rifts of California first took place. Although profound regional subsidence was the rule in central and portions of southern California, local movements along the faults mentioned elevated blocks of the pre-existing formations into islands, usually of considerable relief, in the region now occupied by the Coast Ranges. It is in a study of details such as the distribution of the land and water in these fault zones that composite maps, such as those accompanying this paper, become entirely inadequate and sometimes misleading. Suffice to say that beginning with the pre-Vaqueros (pre-lower Miocene) period of disturbance many of the major blocks within the general fault zone of the Coast Ranges, and to a lesser extent, the minor blocks within the major masses, were seldom at rest for more than relatively short periods up to the present day. Some folding took place during the pre-Vaqueros period, but it was local in character, such as that exhibited in the Coalinga district, and of minor importance as compared with the vertical movements of the large masses. One of the most significant facts in connection with the lower Miocene subsidence was the retention of its position above sea-level of the Sacramento Valley region at a time when the San Joaquin Valley to the south was subjected to marine conditions. This discordance of movement between the two ends of a continuous basin, which in the discussion of California

geology has heretofore been considered as a unit, is believed to be related to the positive or upward-tending forces accompanying or immediately preceding the important volcanic activity which took place during early Miocene[1] time adjacent to the Sacramento Valley, and northward into Washington, but which are absent or insignificant in the region contiguous to the San Joaquin. In this connection it is also worthy of note that the greater part of the Willamette Valley was also out of water during the lower Miocene.[2]

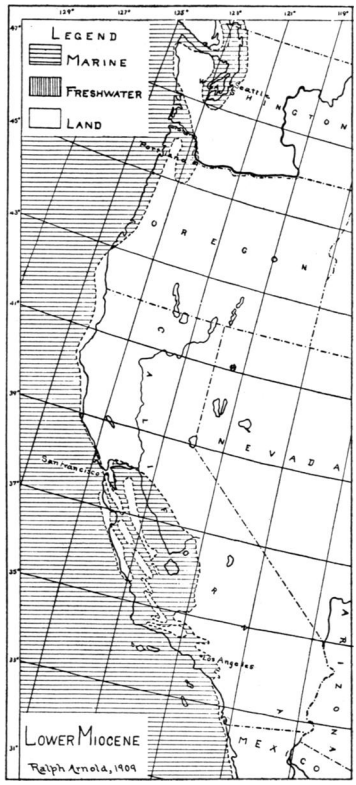

FIG. 3.—Map showing hypothetical distribution of land and water on the Pacific Coast during lower Miocene time.

DISTRIBUTION AND CHARACTER OF SEDIMENTS

The Vaqueros or lower Miocene proper, and the Monterey or lower middle Miocene epochs have been included in mapping and discussing the lower Miocene, for together they mark by subsidence the beginning of a new geologic cycle following the Oligocene elevation. Locally the Vaqueros and Monterey have totally unlike histories. The Vaqueros in the Coast Ranges of central California is characteristically conglomeratic at the base, and sandy, with minor quantities of shale, in its upper portion. In the northern part of southern California it is largely dark arenaceous shale associated with minor quantities of sandstone. The Monterey, on the other hand, is composed largely of diatomaceous material with minor quantities of sandstone, fine volcanic ejectamenta, and limestone, the last three

[1] J. C. Merriam, *Bull. Dept. Geol. Univ. Cal.*, Vol. V, p. 173.

[2] Oral communication from Mr. Chester W. Washburne.

usually more noticeable toward the base. The Modelo formation of Ventura County, the probable equivalent of the Monterey, contains two important coarse sandstone zones. In the region of Mount Diablo the Vaqueros and Monterey formations comprise alternations of sandstone and shale. In Washington and Oregon the whole lower Micoene is largely sandstone with some associated shale. A gradual gradation between the two formations is the rule, although their contact is often sharply marked and in some places is an angular unconformity.[1] The thickness of the Vaqueros is as much as 3,000 feet, that of the Monterey over 5,000 feet, a total for the whole of the lower half of the Miocene of over 8,000 feet.

CONDITIONS OF DEPOSITION

The deposition of the lower Miocéne (Vaqueros) sediments was inaugurated over much of the submerged territory, along the shores of islands of sharp relief. Erosion and deposition were rapid within local basins, especially in the region from the Santa Cruz Mountains southward to San Luis Obispo County, and still there were localities within these areas of intense sedimentation where deposition was slow. It is the belief of the writer that these variations were dependent, at least in part, on the positions of the areas in question relative to the steep or low slopes of tilted fault blocks.

Over those portions of southern California, such for instance as in Ventura County, where the sea supposedly occupied the present land-area during the Oligocene, the conditions during the Vaqueros (lower Miocene) were quite different from those northward in the Coast Range archipelago. Instead of the littoral conditions accompanied by rapid and coarse sedimentation of the latter province there was in the Ventura County area deep water with slower deposition and finer sediments, especially in the earlier Miocene.

The lower middle Miocene (Monterey) shale formation is one of striking individuality, and conditions of unusual character prevailed during its period of deposition.[2] The land which had begun to subside at the beginning of Miocene time, later, at the inauguration of the middle Miocene, sank over a large part of the region of Cali-

[1] Branner, Newsom, and Arnold, *Santa Cruz Folio.*

[2] For a fuller description of the Monterey see A. C. Lawson and J. D. L. C. Posada, *Bull. Dept. Geol. Univ. Cal.*, Vol. I, pp. 22 ff.; H. W. Fairbanks, *ibid.*, Vol. II, pp. 9 ff.; Ralph Arnold and Robert Anderson, *U. S. Geol. Survey Bull. 322*, pp. 35 ff.

fornia now occupied by the Coast Ranges and fairly deep water conditions became prevalent. A large area embraced between the Salinas and San Joaquin valleys and extending northward from the Antelope and Cholame valleys well toward the Livermore Valley was an exception to this general subsidence, and although much of it had been under water in Vaqueros time it was probably dry land or at least an area not subject to sedimentation during the Monterey. The wearing-away of extended land-areas ceased as they became submerged, and the material for the formation of coarse detrital deposits was no longer plentiful. Although the total thickness of the Monterey approximates a mile it is not probable that the depth of the sea at any time was as much as this, being more likely closer to half a mile.

During the period of transition between the Vaqueros and the Monterey, limestone was formed chiefly, but somewhat inclosed basins where deposits of alkaline mud were laid down apparently existed in places. Such a basin is indicated by the alkaline gypsiferous clays on the south side of the Casmalia Hills, in northwestern Santa Barbara County, probably representing upper Vaqueros.

During the early part of the middle Miocene (Monterey) time conditions were variable, calcareous and siliceous deposits alternating, probably as a result of alternating temporary predominance in the sea of organisms with calcareous or siliceous shells. As the period progressed the siliceous organisms became more predominant and remained so, making up a large fraction of the total bulk of the Monterey formation. It was an age of diatoms. These small marine plants lived in extreme abundance in the sea and fell in showers with their siliceous tests to add to the accumulating ooze of the ocean bottom, just as they are forming ooze at the present day in some oceanic waters. It is well known that diatoms multiply with extreme rapidity. It has been calculated that, starting with a single individual, the offspring may number 1,000,000 within a month. One can conceive that under very favorable life conditions, such as must have existed, the diatom frustules may have accumulated rapidly at the sea bottom and aided the fine siliceous and argillaceous sediments in the quick building-up of the thick deposits of middle Miocene time, some of which are a mile through. These diatomaceous shales are the source of some of the richest petroleum deposits of California.

VOLCANIC ACTIVITY IN THE LOWER MIOCENE

The most important display of volcanic phenomena on the Pacific Coast took place during the early and middle Miocene, and probably reached its climax at the time of the widespread post-early middle Miocene (post-Monterey) disturbances. Great volcanoes were active throughout eastern Washington and Oregon and in the Coast Ranges of California from the Santa Cruz Mountains at least as far south as the Santa Ana Mountains in Orange County. The lavas and tuffs emitted by these volcanoes, and the associated intrusions, were basic in character. Certain facies of the Monterey are believed by Lawson and Posada[1] to consist of fine volcanic ash ejected from distant volcanoes of the period.

FAUNAS AND CLIMATE OF THE LOWER MIOCENE

The marine faunas of the lower Miocene or Vaqueros are well known and of widespread occurrence in the Coast Ranges of California; those of the Monterey, owing to the peculiar character of its sediments, are meager and little understood. A general survey of the fauna, however, indicates conditions approximate to those now existing in the coastal provinces, although certain forms of southern extraction, such as large cone shells, numerous arcas, and other types, indicate possible warmer environment. The evidence of the mollusks is supported by that of the plant remains, at least in so far as it relates to the region of Puget Sound, for there, according to Knowlton,[2] the presence of sumacs, chestnuts, birches, and sycamores in the upper Puget group [probable lower Miocene] would seem to indicate an approach from the subtropical conditions of the Eocene to the conditions prevailing at the present day.

PERIOD OF DIASTROPHISM IN THE MIDDLE MIOCENE

One of the most widespread and important periods of diastrophism in the Tertiary history of the Pacific Coast was that immediately following the deposition of the Monterey or lower middle Miocene. Its effects are visible from Puget Sound to southern California. It is marked as much by readjustment, by local faulting and folding as by general movements of elevation and subsidence. In some regions the

[1] *Bull. Dept. Geol. Univ. Cal.*, Vol. I, pp. 24 ff.

[2] *Tacoma Folio*, p. 3.

folding and faulting were intense, the greatest disturbances accompanying the uplift of the mountain ranges to an altitude of thousands of feet. In other regions low broad folds were formed during the post-Monterey disturbance, and the strata were not upheaved to a great altitude. Faulting on a most magnificent scale took place along the earthquake rift and certain other fault-zones, especially that in the Salinas Valley, and along these lines of displacement, masses of granitic rocks, which during the preceding epoch had been subject to little or no erosion, were suddenly thrust upward and left exposed to the ravages of streams that assumed the proportions of torrents in certain regions, as for instance adjacent to the Carrizo Plain in south-central California. The post-Monterey disatrophic movements in the Puget Sound province also produced sharp relief as is evidenced by the coarse sediments deposited immediately following the disturbance. The localization of movement during the period is exemplified at numerous localities in the Coast Ranges.

Throughout much of the coastal belt, and probably likewise in the interior, great volcanic activity took place during the middle Miocene, this being the last epoch of volcanism in the Coast Ranges south of San Francisco. During this post-Monterey period of diastrophism general subsidence took place over most of the areas which were under water during the lower Miocene, and, in addition, extended northward from San Francisco Bay into the Sacramento Valley and along the coast to the California-Oregon line and southward down the Willamette Valley of Oregon. A new channel was apparently opened across the northwestern end of the Olympic Peninsula, and the Colorado Desert country of southern California and Arizona which for a very long time had presumably been free from marine conditions was occupied by an arm of the sea.

THE UPPER MIOCENE PERIOD

DISTRIBUTION AND CONDITIONS OF DEPOSITION

With the possible exception of that in the Eocene the subsidence immediately preceding and extending into the upper Miocene was the most important in the Tertiary history of the Pacific Coast. As a result, the formations of this epoch occupy a very considerable percentage of the surface of the present land-area. The sediments

in the southern Coast Ranges, especially, are largely derived from granitic rocks and are usually coarser at the base, becoming finer and finer toward the top, possibly indicating a subsidence greater than the concomitant sedimentation. Exceptions to the rule of coarse basal sediments are not uncommon, however, and in the Santa Cruz Mountains and also in eastern Monterey County, Cal., the unconformable deposition of fine shale directly upon older rocks is a well-marked phenomenon. This, of course, indicated a sudden and rather deep submergence of the areas in question at the initi ation of the upper Miocene. Conditions favoring the life of diatoms, so marked in the Monterey, continued over part of the Monterey diatomaceous shale territory during the upper Miocene (Santa Margarita and Fernando formations). The areas of maximum deposition during the period were apparently on the southwestern side of the San Joaquin Valley in western Fresno County and in central Ventura County, Cal., where thicknesses of over 8,000 feet of sediments, belonging largely to the upper Miocene, occur.

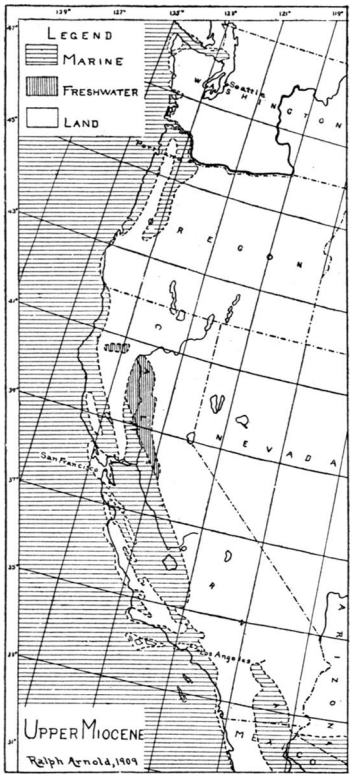

FIG. 4.—Map showing hypothetical distribution of land and water on the Pacific Coast during upper Miocene time.

EROSION AND VOLCANIC ACTIVITY

The peneplanation of the Klamath Mountains and the Sierra Nevada was probably completed during the upper Miocene, the detrital material from these land areas forming the great deposits in the San Joaquin and Sacramento valleys and the coastal belt of northern California. Erosion was practically continuous in these

first-mentioned areas from the beginning of the Eocene, but the final approach toward base level was probably not attained until the close of the upper Miocene. Volcanic activity had ceased on the Coast Ranges south of San Francisco during the inauguration of the upper Miocene, and had become subdued if not suppressed in the coastal belt to the north. In Oregon[1] and possibly also in the vicinity of Mount Diablo, east of San Francisco, in northeastern California, and in Washington volcanoes still persisted.

FAUNAS AND CLIMATE OF THE UPPER MIOCENE

The upper Miocene as here mapped and described embraces several formations, each carrying a more or less well-defined fauna. The most characteristic of these, in the order of age, are the Santa Margarita, typically developed in San Luis Obispo and Monterey counties, Cal., the Empire of Oregon, and the San Pablo of the San Joaquin Valley. All three of these indicate conditions approaching those of the present day, though leaning toward warmer climates. Toward the end of the Miocene and the beginning of the Pliocene, the forerunners of the upper Pliocene sub-boreal invasion which was to come, began to be felt. A cool-water fauna is found in the uppermost Etchegoin (upper Miocene) formation in the Coalinga district, this being followed by a freshwater fauna. In the lower Pliocene faunas of southern California are the last representatives of certain unique species of Pecten which were abundant in the upper Miocene of central California, but which migrated southward during the late Miocene, and became extinct before the Pliocene in the territory where they formerly had been so abundant. The abundance of huge oysters, pectens, and certain subtropical echinoid types in the Santa Margarita implies shallow, rather warm, water—these conditions being due in part, at least, to the local sheltered bodies of water which occupied the southern Coast Ranges during that period. The Empire fauna, best developed along the edge of the open upper Miocene ocean, extended from at least as far north as the Straits of Fuca to the region of the Santa Cruz Mountains and possibly farther south.

The strong resemblance between the Etchegoin fauna of the

[1] J. C. Merriam, *Bull. Dept. Geol. Univ. Cal.*, Vol. V, p. 173.

Kettleman Hills in southern Fresno County, Cal., and the Carrizo Creek beds of the Gulf province of southeastern California has led to the correlation of the latter with the former, although the writer's first examination of the Carrizo Creek fossils led to his placing them tentatively in the lower Miocene.[1] This correlation of the beds with the upper Miocene seems best to fit the conclusions based on other criteria such as faunal relations, character of sediments, sequence of geologic events in this province, etc.

THE PLIOCENE AND QUATERNARY PERIODS

CONDITIONS OF DEPOSITION AND CHARACTER OF SEDIMENTS

Sedimentation was continuous from the Miocene through the Pliocene and on into the Quaternary over large areas along the Pacific Coast, but there was a marked change in the conditions surrounding the deposition at various times within this long period. In a limited coastal belt, marine conditions marked the Pliocene and Quaternary as well as the upper Miocene, while farther inland freshwater, possibly alternating with short brackish-water or even marine, conditions prevailed during the Pliocene and Quarternary. This change from marine to lacustrine environment in the basin provinces of the Coast Ranges was probably brought about by two causes: first, a gradual elevation of the whole coast, and second, as suggested by Newsom,[2] movements along the earthquake rift and other faults in which certain of the blocks were elevated, forming barriers across pre-existing channels between the interior basins and the ocean. Faunal evidence indicates that those basins farthest inland, such as the San Joaquin Valley, became fresh possibly earlier in the Pliocene than those nearer the sea, such as the Santa Clara Valley basin.

The marine Pliocene deposits consist largely of fine sand and soft shale, and sometimes marl, while the freshwater sediments usually include considerable thicknesses of coarse, more or less incoherent gravels, hardened silt and sands. The maximum thickness of the marine Pliocene is attained in the Merced section immediately south of San Francisco, where approximately 4,000 feet of strata of Pliocene age are exposed. The greatest thickness of freshwater

[1] *Science*, N. S., Vol. XIX, 1904, p. 503.

[2] "Santa Cruz Folio," *Geologic Atlas U. S.*, 1909.

Pliocene occurs along the southwestern border of the San Joaquin Valley in western Fresno and Kings counties where the Tulare formation, largely of Pliocene age, attains a thickness of about 3,000 feet.

DIASTROPHISM AND VOLCANISM IN THE PLIOCENE

The most important movements inaugurating the Pliocene seem to have been an elevation of the Sacramento Valley and certain portions of the coastal belt of northern California and Oregon and the closing of the connection between the south end of the San Joaquin Valley and the southern California province. Although sedimentation was practically continuous from the Pliocene into the lowest part of the Pleistocene over much of the Pacific Coast, there is in parts of southern California a sharp line of unconformity between the Pliocene and Pleistocene. The extreme localization of the movements producing this unconformity is well exemplified at San Pedro, near Los Angeles, where the Pleistocene is separated from the Pliocene by an angular unconformity at Deadman Island, while half a mile distant on the mainland the same formations are perfectly conformable. Volcanic activities of a more or less complicated nature took place in certain portions of northern and central California during the Pliocene, while in the same period and probably up to a very recent date certain areas in the Sierra Nevada and Cascades have felt the effect of volcanism to a marked degree.

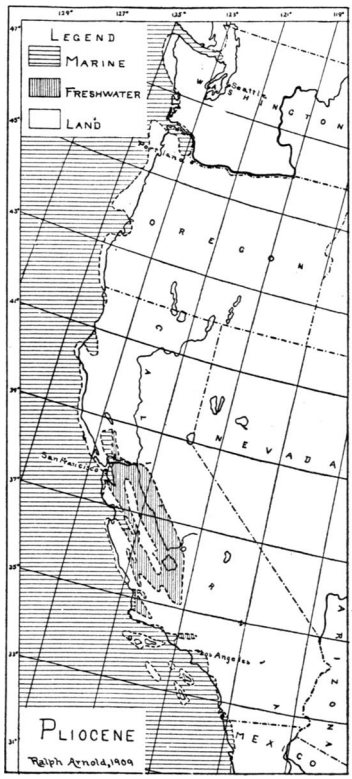

FIG. 5.—Map showing hypothetical distribution of land and water on the Pacific Coast during Pliocene time.

DIASTROPHISM IN THE QUATERNARY

Important and more or less widespread periods of diastrophism later than the one terminating the Monterey (middle Miocene) period of deposition occur in the Pleistocene. Up to the time of the discovery of certain indisputable evidence[1] regarding the Pleistocene age of beds affected by certain of these latest mountain-forming movements, the diastrophism had been considered as closing the Pliocene and initiating the Pleistocene. Minor movements producing local unconformities took place in central and southern California at various times during the Pleistocene in addition to the more far-reaching disturbances in the same epoch. The latest diastrophism, including the elevations and subsidences of the coast line, the recent movements along the earthquake rift, etc., are familiar to all. The localization of many of these movements is known already; the localization of many more of them will, it is believed, become clear when they are studied in detail.

FAUNAS AND CLIMATE OF THE PLIOCENE AND PLEISTOCENE

The faunas of the Pliocene and Pleistocene freshwater deposits are closely related and in some cases almost identical to the living faunas of the same province, while the marine faunas, on the other hand, indicate profound variation of environment, at least as regards temperature. Dr. Philip P. Carpenter[2] was the first to point out the cold-water faunas of the upper Pliocene and lower Pleistocene of the Pacific Coast. His conclusions have been strengthened by later workers, and in addition it has been shown that the latest Pleistocene faunas of the same region are of a type more tropical than those now inhabiting the shores of the Pacific Coast of the United States. It is thus evident that the warm temperature of the upper Miocene gave place to cooler conditions just before or at the beginning of the lower Pliocene, and to sub-boreal conditions in the upper Pliocene and lower Pleistocene. The later Pleistocene showed a very marked increase in oceanic temperature over the lower Pleistocene, even approaching subtropical warmth, and this, in turn, being followed by the conditions now prevailing. At some time during the upper

[1] *Mem. Cal. Acad. Sci.*, Vol. III, 1903, pp. 53–55.

[2] *Ann. and Mag. Nat. Hist.*, 3d Ser., Vol. XVII, 1866, p. 275.

Miocene and Pliocene, conditions prevailed favoring the migration of similar faunas into Japan and California or intermigration between the two. This is shown by the close similarity of certain pectens found in the upper Miocene in California, in still later beds in Alaska, and in the living fauna of Japan. The general resemblance of the late Tertiary faunas of California and Japan also favors this conclusion.

SUMMARY AND CONCLUSIONS

SUMMARY

Following the period of elevation and erosion at the close of the Cretaceous, the Eocene was inaugurated by a subsidence below sea-level of the greater part of western Washington and Oregon and the western part of central and southern California. Volcanic activity was pronounced in the early and middle Eocene. Later in the Eocene brackish- and freshwater conditions prevailed over the same area, and extended over much of Alaska. The fauna and flora of the Eocene were tropical to subtropical. The Oligocene was a period of elevation with marine conditions restricted to a much smaller area than in the Eocene. The fauna was transitional with stronger affinities toward the Miocene. The lower Miocene marked a widespread subsidence in the coastal belt which was followed by a period of mountain building and great local deformation, volcanism, etc. The Miocene faunas and floras indicate conditions comparable with those of the present day, or possibly a little warmer, except at the very close, when cool conditions began to prevail. The upper Miocene was a period of subsidence, with ideal conditions for maximum deposition of sediments in local basins. During Pliocene and early Pleistocene time there was a continuation of many of the upper Miocene conditions, except that marine environment gave place locally to freshwater. The marine fauna of the upper Pliocene and lower Pleistocene indicates sub-boreal conditions in southern California, followed by conditions in the middle or later Pleistocene more tropical than those of today. A period of elevation and considerable local deformation in the early Pleistocene inaugurated the present conditions on the Pacific Coast. Many of the movements occurring throughout the Tertiary were of local extent, and, for that reason,

correlation on a basis of diastrophism, unsupported by paleontologic evidence, is extremely hazardous.

CYCLES OF DIASTROPHISM

The period of the Tertiary uplift of the last worldwide cycle of diastrophism has been marked by two complete subcycles in the Pacific Coast of North America. The first was begun with gradual submergence in early Eocene, was continued by a gradual elevation in the later Eocene when marine conditions gave place to brackish- or freshwater conditions, and was completed by the epoch of uplift and erosion in the Oligocene. The second was initiated by submergence in the Miocene, was continued by the gradual elevation in the Pliocene, when, as in the later Eocene, freshwater conditions supplanted marine, and has been practically completed by the Quaternary uplift which marks the present position of the continent.

PERIODS OF MAXIMUM ELEVATION AND SUBSIDENCE

The periods of marked elevation were the Oligocene, late Pliocene, and Quaternary; the periods of maximum subsidence were the middle Eocene and upper Miocene; the periods of greatest volcanic activity were the middle Eocene and the middle Miocene. It is noteworthy that the periods of maximum volcanic activity were practically coincident with the periods of maximum subsidence in adjacent areas.

CHANGES IN CLIMATE

The climate was tropical to subtropical in the Eocene, transitional from this to warm temperate in the Oligocene, warm temperate in the Miocene, transitional from this to sub-boreal in the lower Pliocene, sub-boreal in the upper Pliocene and lower Pleistocene, and warm temperate in the later Pleistocene.

DIASTROPHIC PROVINCES

The study of the Tertiary history of the Pacific Coast shows the following positive elements or areas of persistent uplift in the coastal belt: The Olympic Mountains; a more or less uncertain, probably disconnected, belt along the western part of Washington and Oregon; the region of the California-Oregon line and thence eastward toward the Blue Mountains of southeastern Washington; the Santa Lucia Range, south of Monterey Bay; the region north and northeast of

Table of Tentative Correlations of th
Ra

			Standard California Section	Central Washington	Western Washington	Eastern Oregon	Western Oregon	Mount Reg
		Recent	Alluvium	Alluvium	Alluvium	Alluvium	Alluvium	Allu
Cenozoic	Quaternary	Pleistocene	San Pedro Unconf.—└Unconf.		Vashon Admiralty		Marine Sands	Marine Sa —Unconforn
	Tertiary	Pliocene	Merced San Diego			Rattlesnake		"Siestan" —Unconforn "Orindan"
					—Unconformity—	—Unconformity—		
		Miocene	San Pablo —Unconformity— Santa Margarita	Ellensburg	Beds at Clallam Bay, Quillayute River, Sooke beds		Empire	San Pablo (Ione?) Beds in Contra Co
			—Unconformity— Monterey —Unconformity—	Yakima Basalt	—Unconformity— Beds at Port Blakeley, Fuca Strait	Columbia River Basalt	Astoria Group: "Astoria" sandstone	—Unconforn Monterey
			Vaqueros		Group: Beds at Porter, Bean Point, Fuca Strait, etc.			Vaqueros
		Oligocene	—Unconformity— San Lorenzo			—Unconformity— John Day	"Astoria" shale Oakland (?)	
			—Unconformity(?)—	—Unconformity—		—Unconformity—	Tyee	
		Eocene	Tejon	Manastash —Unconformity—	Puget Group: Beds at Little Falls (freshwater)	Clarno	Coaledo — Arago	Tejon
			Martinez	Roslyn —Unconformity— Swauk	Beds at Little Falls (marine) Beds at Port Crescent		"Pulaski" Umpqua	Martinez
			—Unconformity—	—Unconformity—		—Unconformity—	—Unconformity—	
Mesozoic	Cretaceous	Upper Cret.	Chico			Chico	Chico	Chico
		Lower Cret.					Shasta ("Myrtle")	

ıe Tertiary Formations of California, Oregon, and Washington
lph Arnold—January, 1909

Diablo gion	Santa Cruz Mountains	San Luis Folio	Santa Maria District	Coalinga District	Ventura County	Los Angeles County	
vium	Alluvium	Alluvium	Alluvium	Alluvium	Alluvium	Alluvium	
nds nity—	Marine Sand —Unconformity—	Marine Sands —Unconformity—	Marine Sands —Unconformity—	Stream Deposits	—Unconformity—	San Pedro —Unconformity—	San —Unco
nity—	{ Merced { Santa Clara	Paso Robles		Tulare		Beds at Deadman Is.	
,,	Purisima		Fernando		Fernando	Beds at Third St. Tunnel and Temescal Canyon	Fernando San
		—Unconformity—		—Unconformity— Etchegoin —Unconformity—			Beds Carri
sta County	Santa Margarita	{ Pismo { Santa Margarita		Jacolitos Santa Margarita			
nity—	—Unconformity—	—Unconformity—	—Unconformity—		—Unconformity—	—Unconformity—	
	Monterey	Monterey	Monterey		Modelo		
	—Unconformity—			—Unconformity—			
	Vaqueros	Vaqueros	Vaqueros	Vaqueros	Vaqueros	Puente	
	—Unconformity—			—Unconformity—			
	San Lorenzo		Sespe (Oligocene ?)		Sespe (Oligocene ?)	Sespe (Oligocene ?)	—Unco
			Tejon	Tejon			
					Topatopa		Mart or Te
	Limestone inclusions in diabase						
		—Unconformity—					
	Chico	Chico		Chico		Chico	
			Knoxville				

	San Luis Folio	Santa Maria District	Coalinga District	Ventura County	Los Angeles County	San Diego Region
	Alluvium	Alluvium	Alluvium	Alluvium	Alluvium	Alluvium
	Marine Sands —Unconformity—	Marine Sands —Unconformity—	Stream Deposits	—Unconformity—	San Pedro —Unconformity—	San Pedro —Unconformity—
	Paso Robles	Fernando	Tulare	Fernando	Beds at Deadman Is. Beds at Third St. Tunnel and Temescal Canyon Fernando	San Diego
			—Unconformity—			Beds at Carrizo Creek
	—Unconformity—		Etchegoin —Unconformity—			
a	{ Pismo { Santa Margarita		Jacolitos Santa Margarita			
	—Unconformity—	—Unconformity—		—Unconformity—	—Unconformity—	
	Monterey	Monterey		Modelo		
			—Unconformity—			
	Vaqueros	Vaqueros	Vaqueros —Unconformity—	Vaqueros	Puente	
		Sespe (Oligocene?)		Sespe (Oligocene?)	Sespe (Oligocene?)	
						—Unconformity—
		Tejon	Tejon			
				Topatopa		Martinez or Tejon
usions						
	—Unconformity—					
	Chico		Chico		Chico	
		Knoxville				

San Diego; and the Peninsula of Lower California. The Sierra Nevada and Sierra Madre and San Bernardino and San Jacinto mountains may also be considered in the same class. The region of Santa Catalina and San Clemente islands off southern California belong to an area about which little is known previous to the Miocene, although it is the belief of the writer that they are in a belt of more or less persistent uplift.

The negative elements or areas of persistent subsidence are: Puget Sound; the Willamette Valley; the San Joaquin Valley, and the Sacramento Valley to a less degree; central Ventura County; and, since the Eocene, the Salinas Valley, and the vicinity of Los Angeles.